Visualization of Numerical Unsteady Fluid Flows

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ABSTRACT

Instantaneous streamlines are commonly used to visualize particle paths in steady flows. It is shown, however, that streaklines are often more appropriate for unsteady flows. The typical size of unsteady flow simulations makes interactive visualization difficult if not impossible. Two common approaches for visualizing unsteady flows are described. The advantages and disadvantages of each are discussed. Many visualization systems have been developed for steady flows, yet relatively few have been developed specifically for those that are unsteady. The system developed at NASA Ames Research Center has produced effective visualization for many unsteady flows. The features of this system are introduced and some results are shown. Future directions are also discussed.

INTRODUCTION

Numerical simulations of complex 3D unsteady flows are becoming increasingly feasible because of the progress in computing systems. Unfortunately, because many existing flow visualization systems were developed for steady solutions, they do not adequately depict those from unsteady flow simulations. Furthermore, most systems only handle one time step of the solution at a time and do not consider time in the calculation. For example, instantaneous streamlines are computed by tracking the particles using one time step of the solution. To compute streaklines, particles need to be tracked through all time steps. Streaklines reveal different information about the flow than that revealed by instantaneous streamlines. A comparison of instantaneous streamlines with dynamic streaklines is shown.

For a complex 3D flow simulation, it is common to generate a grid system with several million grid points and tens of thousands of time steps. The disk requirement for storing the flow data can easily be thousands of gigabytes. Visualizing solutions of this magnitude is a challenge with current disk storage technologies. Even interactive visualization of one time step can be a problem for some existing flow visualization systems because of the grid size. Two approaches for visualizing unsteady flows are described.

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* This work was supported by NASA under contract NAS 2-12961.

The flow visualization system developed at NASA Ames Research Center to compute time-dependent particle traces from 3D unsteady CFD solutions is described. The system performs unsteady particles tracking, and has been used by many scientists to visualize their flows. The capabilities of the system are described, and visualization results are shown.

STREAMLINES VERSUS STREAKLINES

Particle tracking is an effective technique to visualize fluid flows. A streamline is a curve that is tangent to the velocity field at an instant in time [Merzkirch '74]. In experimental flow visualization, streamlines for steady flows can be generated by injecting smoke into the flow. To generate a streamline from numerical flows, a massless particle is released from a fixed location called the seed point and then tracked through the flow. The line representing the path of the particle is the streamline. Because streamlines are computed based on one time step of the flow, they are effective for showing the flow at an instant in time.

A streakline is the line joining the positions of all particles that have been previously released from a seed point. A numerical streakline can be generated by releasing particles continuously from a seed point. The line formed by these particles is the streakline. When comparing photographed streaklines from experimental flow to numerical streaklines, the former is more continuous than the latter. The reason is that numerical streaklines are represented by particles that are released at discrete time steps, whereas a constant stream of smoke is released in experimental flow. A method for generating continuous numerical streaklines is to simply connect adjacent particles to form lines. This method is effective if the flow does not diverge too much and the particles are close together. However, most unsteady flows convolute over time, and particles can become far apart. Nevertheless, discrete streaklines are still very effective for visualizing unsteady flows. If the time interval between the time steps is relatively small, then the streaklines in general will be continuous.

Streamlines and streaklines are identical in steady flows. However, they differ in unsteady flows. Streaklines are most effective for depicting time-varying phenomena in unsteady flows, one reason being that the time variable is considered in the calculation. Figure 1 shows a comparison of streamlines and streaklines near an oscillating airfoil. The numerical simulation for the airfoil is discussed in [Ko & McCroskey '95]. Streamlines only reveal the behavior of the flow at one instant in time, whereas streaklines depict the time evolution of the flow. As shown in Figure 1, streaklines provide a much better representation of the vortices in the flow than that revealed by streamlines. When animated, streaklines effectively reveal time-varying phenomena in the flow; for example, vortex shedding, breakdown, and formation. Though streamlines are the standard method for visualizing steady flows, streaklines should also be computed when visualizing unsteady flows.

Figure 1. A comparison of streamlines (top) and streaklines (bottom).

VISUALIZATION APPROACHES

The problem size of 3D unsteady flow simulation is increasing as the hardware technology continues to improve. It is not unusual to have a grid containing several million points, and the file size for one time step can easily exceed several megabytes. If there are tens of thousands of time steps, then the total disk requirement for storing the entire solution would be thousands of gigabytes. Interactive visualization of this magnitude is clearly impossible with current hardware technology. Presently, two standard approaches are used for visualizing unsteady flows: co-visualization and post-visualization. In the following, graphics objects refer to particle traces (e.g. streaklines and streamlines), isosurfaces, contour lines, and color shaded grid surfaces (e.g. pressure surfaces). Graphics parameters refer to seed points (for particle traces) and threshold levels (for contouring).

Co-Visualization

Visualization is performed concurrently with the flow calculation. If it takes several minutes to compute the solution at each time step, then the graphics objects are usually saved to disk for later playback. The calculation is usually performed on a high-performance computer, while the graphics objects are sent via the network to a graphics workstation.

Co-visualization allows the graphics objects to be computed using all the simulation time steps in the solution. Furthermore, it is not necessary to save the solution to disk. If the time taken to compute each simulation time step is less than a few seconds, then the user can view the particle traces interactively. However, if the graphics parameters need to be changed, then the solution must be re-computed because visualization is coupled with the flow calculation. pV3 is a co-visualization system that provides interactive visualization of time-dependent solutions of moderate size. pV3 also provides a ‘plug-in/out’ feature that allows the scientist to monitor the flow calculation [Haimes ‘94].

Post-Visualization

Although co-visualization allows graphics objects to be computed using all simulation time steps and viewed during flow calculation, often the unsteady solution is too compute-intensive to be visualized interactively. The unsteady solution is usually saved to disk and visualization is uncoupled from flow calculation. The advantage of post-visualization is that the graphics parameters can be changed without recomputing the solution.
A disadvantage is that not all simulation time steps are saved due to the size of the solution. The solution may be saved at every 10th, 20th, etc. time steps. The graphics objects can be displayed interactively as they are computed or saved for later playback. By saving the graphics objects to disk, the scientist can repeatedly playback the graphics objects without recalculation.

Depending on the size of the saved solution, interactive visualization may be possible. If the saved solution fits in memory, then graphics objects can be computed and displayed interactively. Unfortunately, most unsteady solutions are orders of magnitude larger than the physical memory of the current graphics workstations. For example, the V-22 tiltrotor simulation consists of 1,400 time steps in the saved solution and each time step requires approximately 100 megabytes. A high-end graphics workstation with one gigabyte of memory could only hold 100 time steps of the solution. This makes interactive visualization of the entire saved solution impossible. An alternative method is to load the saved solution into memory one time step at a time. Graphics objects are computed at each time step and saved for playback. This method is sometimes performed in batch due to the time it takes to read the solution and to compute the graphics objects. Although this method may seem too slow, it allows the scientists to use all time steps of the saved solution in the calculation without resampling of the solution.

UNSTEADY FLOW ANALYSIS TOOLKIT

The Unsteady Flow Analysis Toolkit (UFAT) was developed at NASA Ames Research Center to assist scientists visualize their unsteady flows. UFAT was developed using the post-visualization method described previously. For visualization purposes, the saved solution is loaded into the memory one time step at a time; and at any time there are at most two time steps in memory. UFAT computes particle traces in unsteady flows with moving grids [Lane ‘94]. The following types of particle traces can be computed using UFAT: streaklines, timelines, streamlines and pathlines. UFAT allows the user to compute

Figure 2. Streaklines about the V-22 tiltrotor aircraft.

particle traces using many time steps. It can assign color values to the particles based on their seed points, time at release, ages, positions, and scalar quantities. UFAT saves the particle traces to a graphics metafile for playback. The graphics metafile is written in a data format that can be displayed by FAST [Bancroft et al. ‘90]. UFAT also computes grid surfaces, vector plots, streamsurfaces, and color shaded grid surfaces. An interactive, distributed version of UFAT will be available in the near future via FAST2. This version of UFAT sends graphics objects to FAST2 as they are being computed. Figure 2 shows streaklines about the V-22 tiltrotor. The unsteady flow simulation of the tiltrotor is discussed in [Meakin ‘93]. The streaklines shown in Figure 2 were computed by UFAT. The figure shows streaklines surrounding the tiltrotor after three blade revolutions.

FUTURE DIRECTIONS

Presently there are very few techniques available for unsteady flow visualization. Some of these include: unsteady particle tracking, vortex core tracking, and surface oil flows. Unsteady particle tracking has been shown to be an effective method for understanding particle paths in unsteady flows. The trajectory path of a vortex core is also helpful in several ways. Techniques for visualizing unsteady surface oil flows are interesting and deserve further investigations. A challenge remaining for the current visualization systems is the magnitude of disk space and memory required for interactive unsteady flow visualization. There is a continuing need to increase the capabilities in memory, computation, and disk technologies.

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